A VERTICALLY INTEGRATED POWER & ENERGY CTA EFFORT TO INSERT A SiC JBS DIODE INTO AN FCS INVERTER CIRCUIT

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ABSTRACT

SiC JBS diodes were developed to replace silicon diodes in a 600A/1200V module integrated into a 3-phase inverter. The module was tested using both types of diodes, and it was shown that the module with the SiC diodes were more efficient. The diodes were developed using modeling techniques, and the procedures for fabricating the diodes were improved by optimizing the ion implant doses and the procedures for activating them.

INTRODUCTION

Hybrid electric vehicles, such as the one in Fig. 1a envisioned for the future combat system (FCS) have, as one of their components, inverter circuits that convert direct current (DC) from batteries into alternating current (AC) used to drive the electric motors. As shown in Fig. 1b, these circuits are composed of transistors used as switches, and diodes to provide a conduction path while a transistor is being turned on, and turned off as quickly as the transistor is turned off. As such, the diodes should have a small forward resistance and be able to be turned off as fast as possible to minimize the loss in the circuit. Because the diodes are handling large amounts of power, they will heat up even if they are efficient, so methods of keeping them cool have to be developed.

Currently, the diodes being used are made out of silicon. Silicon has the disadvantage that it has a relatively small energy gap, E_g, of 1.11 eV. As seen in Fig. 2, this means that, for a given breakdown voltage, V_{BR}, it should have a relatively light doping concentration n_d, because it has a relatively small critical breakdown field, E_C, due to its a relatively small E_g. The small E_g makes it easier to create avalanche breakdown since electron/hole pairs can more easily be created through collisions between charge carriers and the lattice. The small n_d necessitated by the small E_C makes the forward resistance large, as there are fewer electrons to carry the current. In addition, the low doping causes the depletion layer in the diode to be wider, which causes the diode to take a longer time to turn off. Both the larger forward resistance and longer turn off time cause

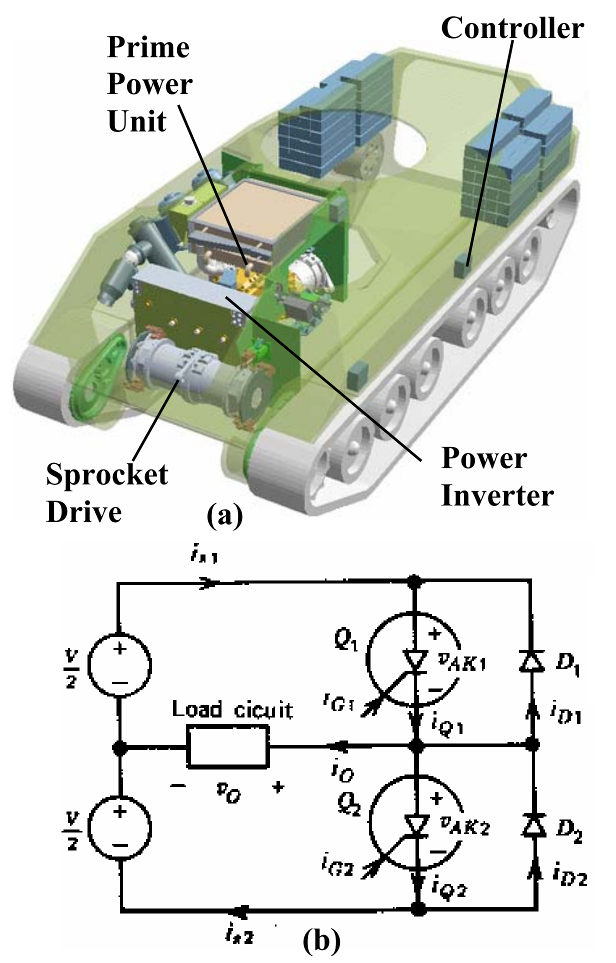

Fig. 1. (a) A hybrid electric vehicle showing a number of electrical systems, and (b) an example of an inverter circuit element used to convert the DC current from the battery to the AC current the systems require.

the circuit to be less efficient. In addition, silicon devices cannot operate above ~150ºC because it has a relatively small energy gap. At higher temperatures electrons can more easily jump from the valence band into the conduction band thereby negating the effects of

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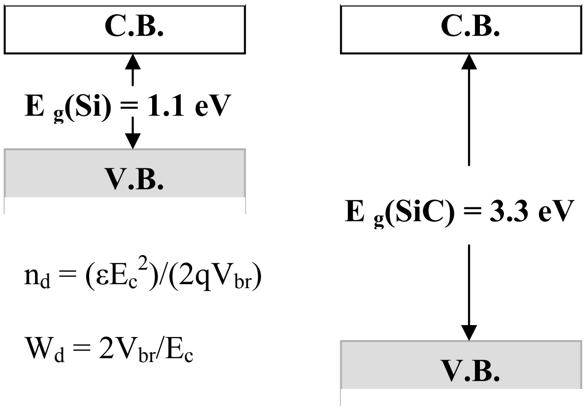

Fig. 2. Schematics of the energy band diagram of Si and SiC, and the equations showing that the semiconductor with the smaller critical field has to be doped more lightly so its depletion layer width will be larger.

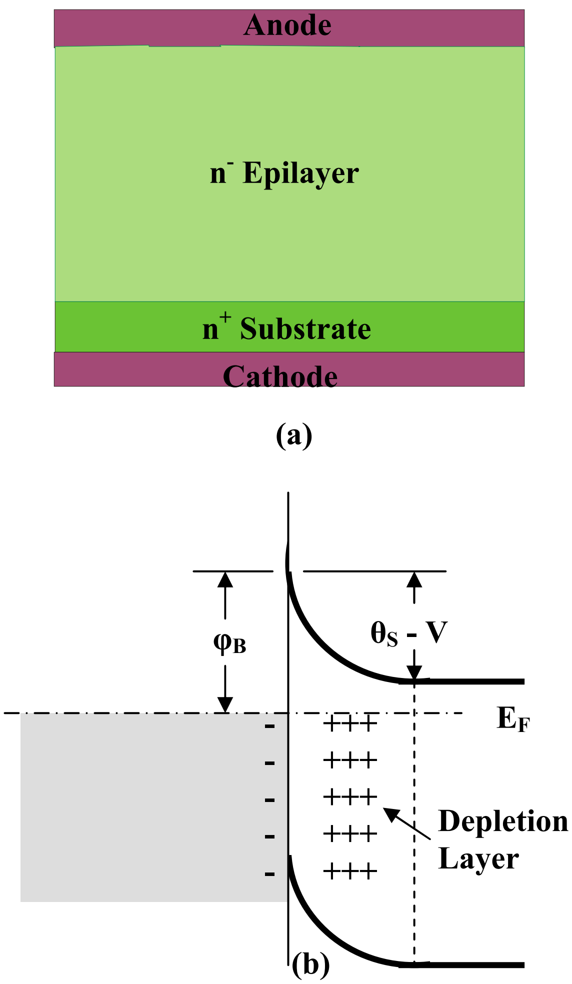

Fig. 3. An (a) schematic and (b) energy level diagram for a Schottky diode.

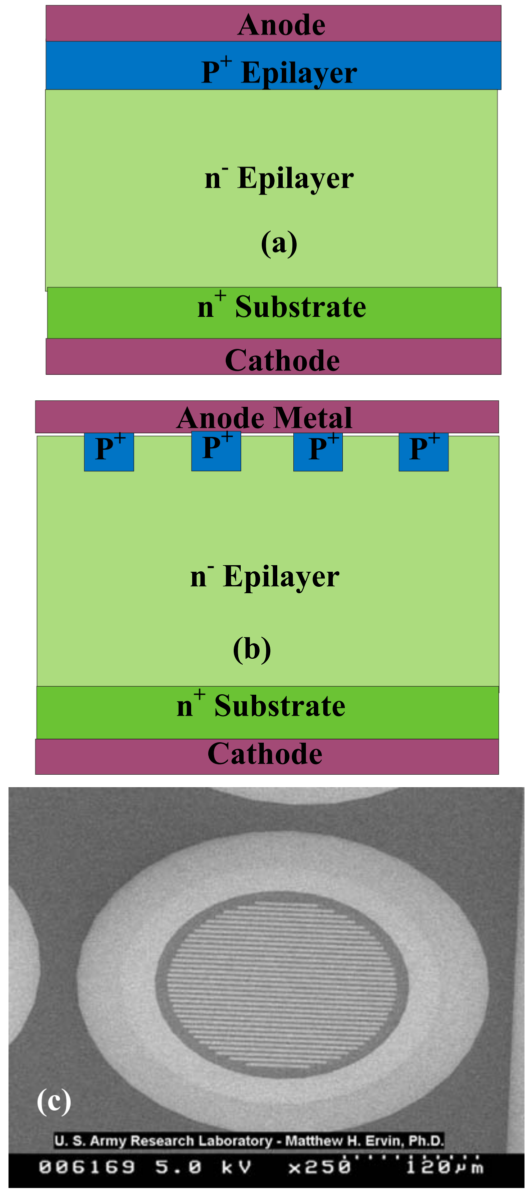

Fig. 4. Schematics of (a) PN and (b) JBS diodes, and (c) a micrograph of an actual JBS diode.

the doping, which then dissolves the p-n junctions. To make matters worse, silicon is a relatively poor thermal conductor so it heats up faster. SiC has the advantage of having a larger energy gap ($E_{g\ 4H\text{-}SiC}$ = 3.26 eV), so diodes made from it can operate faster with lower loss. They also can operate at temperatures well above 150ºC so they can be cooled with engine only thereby eliminating the need for space consuming, noisy cooling systems. SiC also has the benefit that it is a relatively good thermal conductor.

A schematic of a Schottky diode with an n-type semiconductor and its energy level diagram are shown in Fig. 3. The electrons traveling to the left encounter a barrier, $\theta_S - V$, where θ_S is the contact potential and V is the applied potential; it is positive under forward bias and negative under reverse bias. Under forward bias conditions the barrier is lowered so a larger number of electrons moving to the left can make it over the barrier, while under reverse bias, relatively few can. Some electrons can move to the right, but they have to overcome the barrier, φ_B, where φ_B is the difference between the work function for the metal and the semiconductor. The number of electrons that flow over this barrier is unaffected by the applied voltage. Under forward bias the number of electrons moving to the left is so much larger than the number moving to the right, that the latter can essentially be ignored. However under reverse bias when essentially no electrons can move to the left, the number moving to the right is noticed, and it is what is called the reverse saturation current, or the ideal leakage current. Also, under reverse bias, the depletion layer grows as the donor atoms in the depletion layer give up their electrons to the metal to create the potential, $\theta_S - V$. The larger the reverse bias, the wider the depletion layer becomes, and it grows more rapidly in lightly doped semiconductors because there are fewer donors per unit volume to contribute an electron. The depletion layer will continue to grow with the reverse bias until the internal field created by the charge separation exceeds E_C, at which point the diode breaks down.

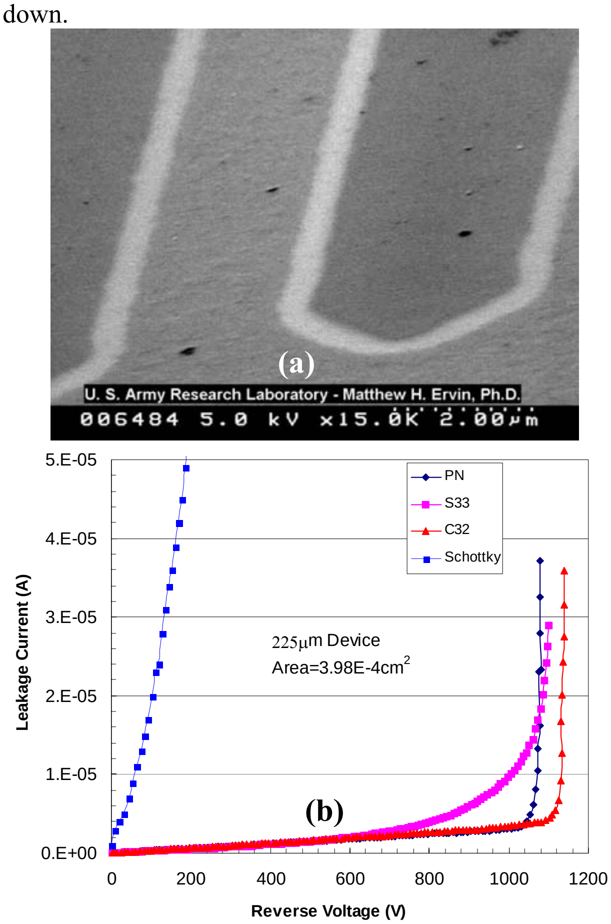

Fig. 5. (a) Micrograph of a JBS diode annealed with an AlN cap, and (b) its reverse i-V characteristics.

The PN diode shown in Fig. 4a operates in a similar way except that the number of electrons flowing to the right is smaller, and holes are injected from the p-type side. The former leads to a lower reverse bias leakage current, while the latter causes the turn-off time to be longer because the injected carriers have to recombine; no such process is required of Schottky diodes because there is only one type of charge carrier. The barrier the electrons moving to the left see is also larger, so the turn on voltage is larger.

Being a series of Schottky and PN diodes connected in parallel the JBS diode shown in Fig 4b attempts to combine the best aspects of both of them while minimizing their negative attributes [Singh, et. al., 2002]. Under forward bias the diode behaves like a Schottky diode because it has a lower turn on voltage. This enables it to turn off quickly because one does not have to be concerned about electron recombination with holes. Under reverse bias the diode behaves like a PN diode because the depletion layer from the P-N junction cuts off flow to the Schottky portion of the diode. This enables the JBS diode to have a lower leakage current.

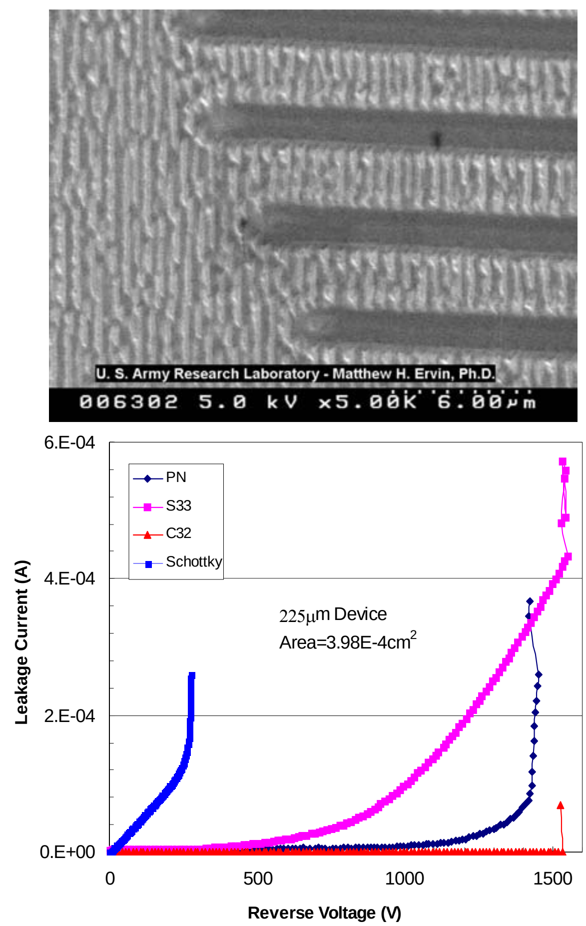

Fig. 6. (a) Micrograph of a JBS diode annealed without an annealing cap, and (b) its reverse i-V characteristics

The JBS diode is fabricated by heavily implanting Al or Al and B to a depth of ~0.5 μm in parallel channels that can be seen in Figs. 4c, 5a, and 6a. These channels have a width, *w*, and they are separated by a distance, *s*, which has to be small enough so that the depletion layers from the adjoining P^+N diodes can pinch off the Schottky diode between them. One of the issues with ion implantation is that the implanted sample has to be annealed so the dopants can diffuse to their equilibrium position and become electrically activated. For SiC, unfortunately this temperature occurs above temperatures at which the silicon evaporates preferentially and roughens the surface. People in industry have attempted to deal with this problem by annealing quickly, annealing in the presence of SiC powder, and annealing in a SiH_4 over pressure, all with limited success. We introduced the idea of annealing with an AlN cap which protects the SiC surface during the anneal, and then can be etched off preferentially in hot KOH [Jones, et. al., 1999]. If the diode has be annealed at a higher temperature, we have deposited BN [Ruppalt, et. al., 2003] on top of the AlN – essentially capping the cap – because the AlN will evaporate. The BN is then ion milled off and the AlN is again etched off; BN is not deposited directly because the ion milling would damage the SiC surface.

That annealing with an AlN cap is beneficial can be seen visually in Figs. 5a and 6a. The diode with the AlN cap shown in Fig. 5a is smooth, while the one annealed without a cap has a very rough surface. Devices made using the cap also have better i-V characteristics as seen in Figs. 5b and 6b, where it is particularly evident that the leakage is larger in the sample that had a 3 μm channel and a 3 μm separation between channels. It was also noted that the yield was much higher for the capped samples. Interestingly, the uncapped samples had a larger V_{BR}. This was attributed to the greater degree of activation in the ion implanted guard rings, as the greater number of silicon vacancies due to the preferential evaporation of silicon enabled the dopants to diffuse to their equilibrium positions faster [Zhu, et. al., 2006].

Annealing the implants does not remove all of the implant induced defects, as is seen in the TEM micrographs in Fig. 7. Persistent defects remain, and some appear to grow in size. These defects have been determined to be stacking faults as shown in Fig. 7b. Further, we have suggested that they are Frank intrinsic stacking faults created by the condensation of divacancies (See Fig. 8.), which have been attributed to the D_I defect [Jones, et. al., 2004], which is a deep donor that can trap out acceptors and act as a scattering center lowering the mobility [Storasta, et. al., 2001]. SiC is particularly vulnerable to these types of defects because it can exist in many different crystal structures called polytypes. The different polytypes are described by the stacking sequence of the basel planes. The example of

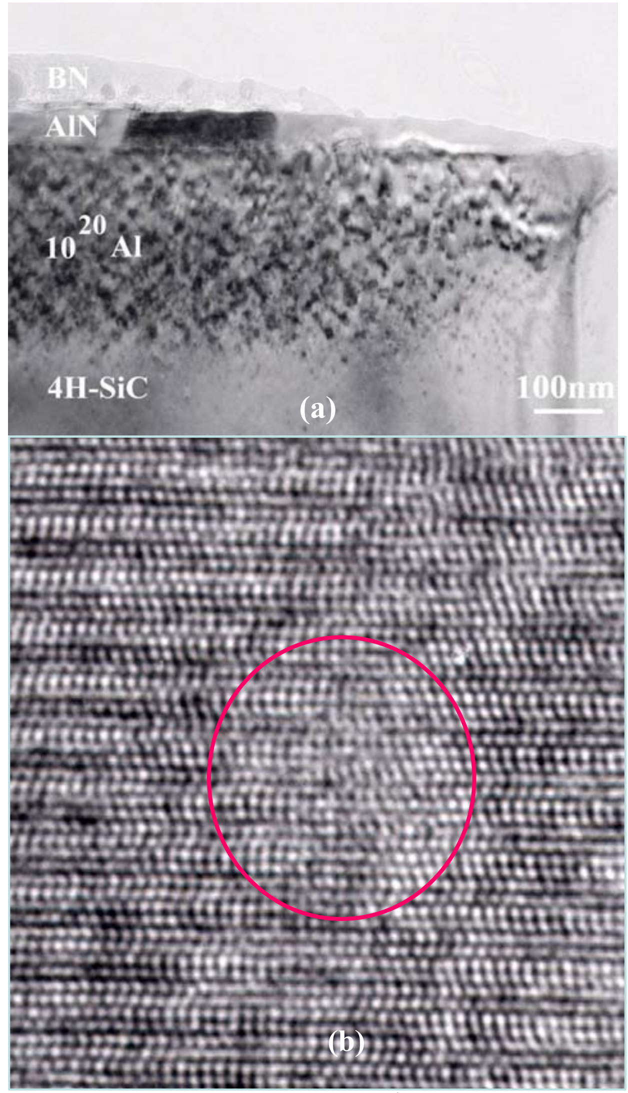

Fig. 7. (a) TEM of an implanted P^+ region showing the persistent ion implanted induced defects (dark regions), and (b) high resolution TEM (HRTEM) of an individual defect showing that it is a stacking fault.

the Frank intrinsic fault shown in Fig. 8b shows how the 4H polytype with an AαBβAαCγ sequence has been converted to the 3C polytype with an AαBβCγ sequence. The fact that we have shown that some of the implant induced defects persist has helped others to explain why defects made from ion implanted structures have characteristics that are inferior to those made from epitaxially grown structures. It has also enabled us to make better devices by engineering around the persistent defect problem. One example is the JBS diode structure shown in Fig. 9. It is generally believed that the P^+ channels should be implanted as heavily as possible for the optimum characteristics. However, we have shown that the concentration of the implant induced defects increases with the concentration. The compromise and the diode with the best characteristics was implanted to 10^{20} cm^{-3} away from the P-N junction where the

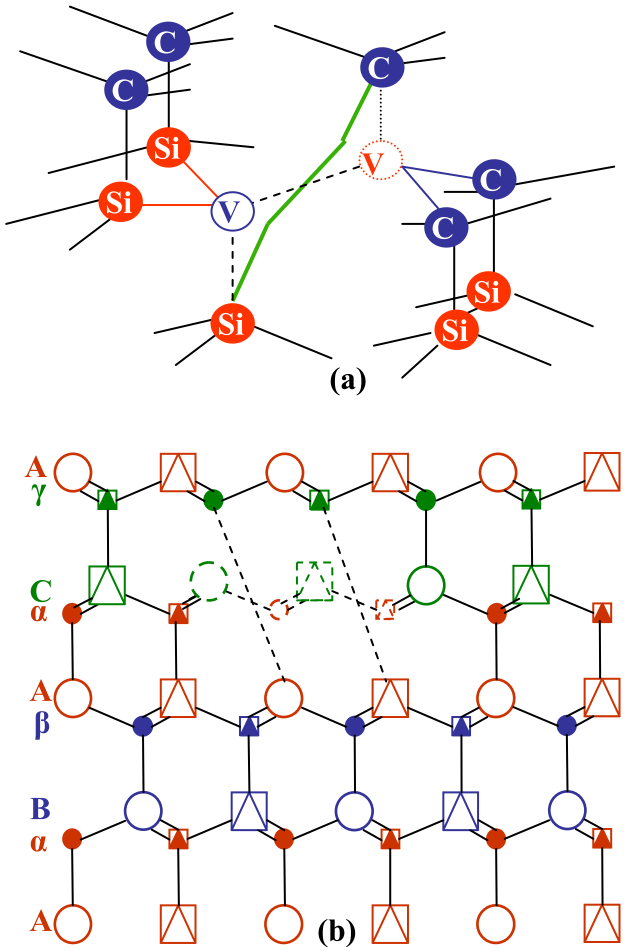

Fig. 8. Schematic of (a) a divacancy formed in ion implanted SiC, and (b) a Frank intrinsic stacking fault in 4H-SiC when the divacancies coalesce on a single plane.

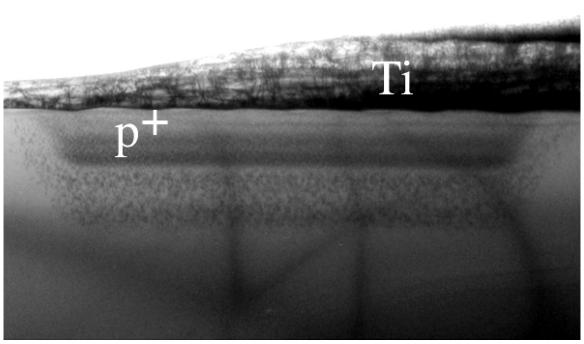

Fig. 9. TEM micrograph of an implanted channel in a JBS diode in which the region near the P-N junction is implanted with less dopants (10^{19} cm^{-3}) than it is in the interior (10^{20} cm^{-3}).

persistent defects would do the least harm, and to 10^{19} cm^{-3} near the junction, where it can be seen in the TEM micrograph that the defect concentration is smaller.

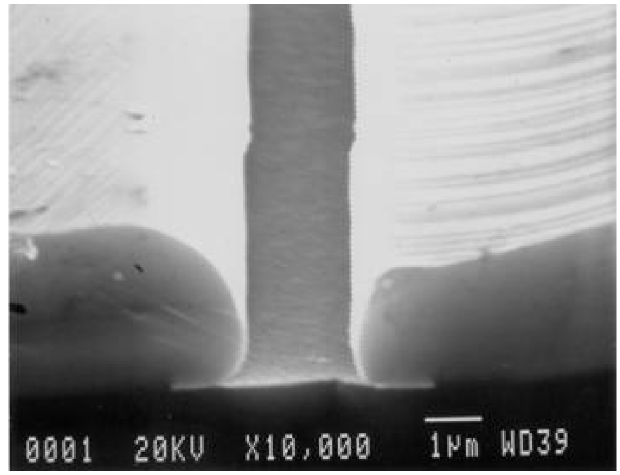

Fig. 10. Regrown channels of a JBS diode that have grown over the protective TaC layer.

An alternative we have begun to investigate is to etch out the channel region and regrow P^+ channels in them using selective area epitaxy [Li, et. al., 2005]. In this process TaC is deposited on the SiC using pulsed laser deposition, patterned and etched, and then put in the growth reactor under conditions where growth will only occur on the exposed SiC; no growth will occur on the TaC. The TaC is then selectively etched of. An example is shown in Fig. 10. Some of the problems are that it is difficult to get the etched out channels defect free, so defects would be grown into the junction. Also, it has not yet been possible to grow back to the exact height so the overgrowth has to be polished off.

We also exploited the ability to regrow on partially processed devices when we fabricated the lateral channel JBS (LC-JBS) diode shown in Fig. 11. The device structure was grown through the N drift-layer, and then it was removed and the base of the P-layer was implanted. The wafer was then returned to the growth furnace and

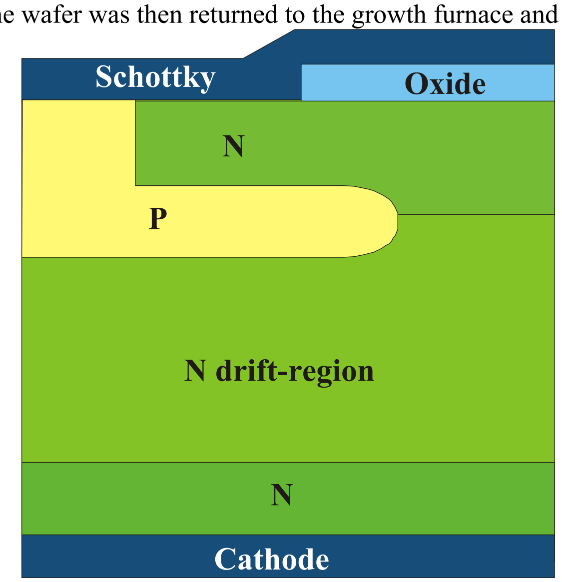

Fig. 11. Schematic of the LC-JBS diode.

the n-layer was grown over the entire wafer; then the underlying P-layer was connected to the top surface by implanting the necks to it. Both implants were annealed at the same time. The reason the diode was designed this way was to be able to more thoroughly pinch off access to the Schottky barrier thereby further reducing the leakage current, while at the same time, not increasing the forward resistance. We were able to fabricate diodes with V_{BR} = 1.5 kV, a forward voltage drop of 1.8 V, and reduce the capacitance by 50% [Zhu, et. al., 2007].

Twelve 25 A SiC JBS 2.5 mm in diameter, or fast silicon, diodes were mounted in a module along with their silicon insulated gate bipolar transistors (IGBT's), as shown in Fig. 12a, and were tested with 600 A flowing through them under a potential of 550 V. The

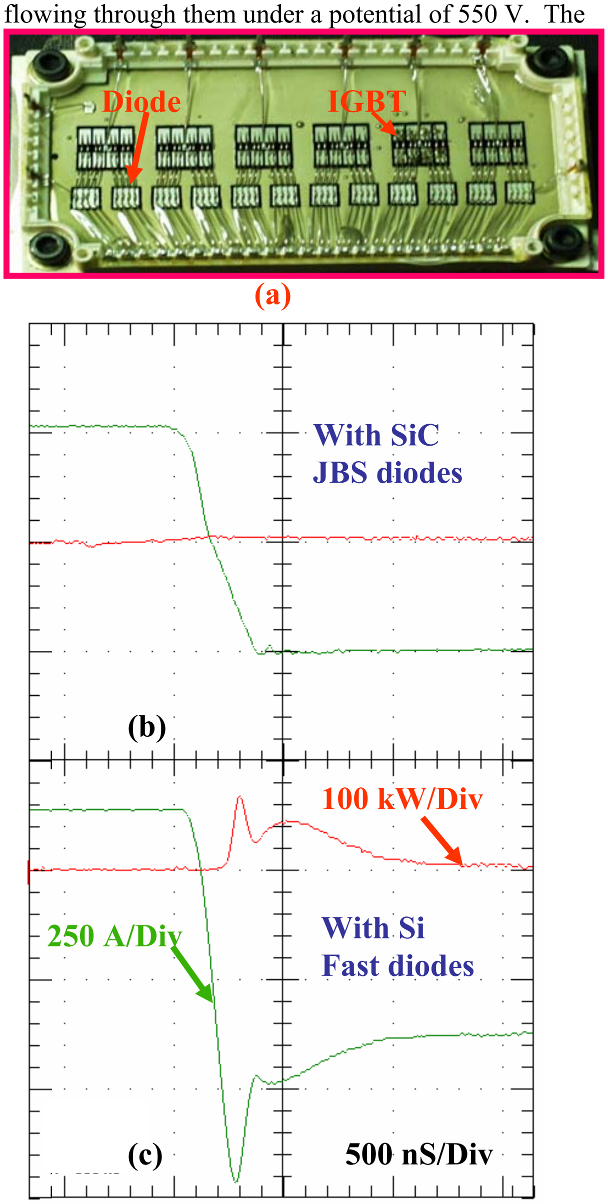

Fig. 12. (a) 600 A / 550 V module containing Si IGBT switches and 25 A JBS SiC or Fast Si diodes, and the module characteristics using the (b) SiC and (c) diodes.

results shown in Figs. 12b,c demonstrate that the module with the SiC JBS diodes is clearly superior, as the reverse current peak, I_{rr}, is only ~ 10 A, the turn-off recovery time, T_{rr} < 50 ns, and there is virtually no stored charge, Q_{rr}. On the other hand, for the module containing the fast silicon diodes, I_{rr} = 340 A, T_{rr} = 500 ns, and Q_{rr} = 86,000 nC. Because the SiC diodes are so much faster, the circuits with these modules can operate up to five times faster – 25 kHz compared to 5 kHz for the modules with the silicon diodes. This would enable one to reduce the passives in the system by a factor of five. The silicon diodes were also less efficient as they generated more heat, which is what the stored charge becomes.

Both circuits do, however, generate heat, and it is important to keep the devices from warming up too much, especially the silicon IGBT's. When SiC IGBT's or bipolar junction transistors (BJT's) become available, they will alleviate the problem somewhat, but it will still persist. Therefore, we have spent a considerable effort designing and testing heat transfer systems, such as the heat sink shown in Fig. 13a. It was composed of a molybdenum plate with copper balls soldered to it and to each other. The coolant was then forced to flow through the tortuous paths created by the soldered copper spheres enabling the coolant to remove a considerable amount of

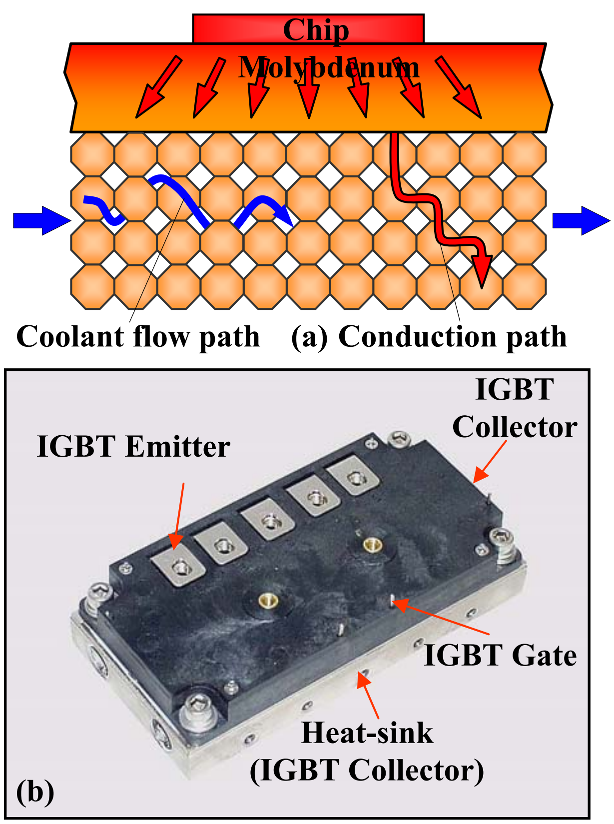

Fig. 13. (a) Heat sink and (b) and IGBT's mounted on a heat sink.

heat. The tortuous path creates thicker boundary layers in the fluid, which enhances the heat transfer, as does the large surface area of the spheres. The spheres connected in all three dimensions do an excellent job of spreading out the heat. The system was designed so that at some time in the future engine oil could be used as the coolant. The engine oil cannot currently be used as the coolant because its temperature is > 150ºC and devices made from silicon, as is the present IGBT switch, cannot operate above this temperature because, as explained earlier, its energy gap is too small.

The ultimate goal was to build 1200 V, 900 A power converter modules that would be used in applications such as an inverter in a hybrid electric vehicle. For the most part, increasing the voltage rating for the diode is done by increasing the length of the N^- layer of the diode shown in Fig. 4. This was done, and the diodes were used in the 1200 V, 500 A module shown in Fig. 14a. Increasing the current carrying capacity is usually done by increasing the cross sectional area of the diode. This seems like a straightforward process, but it is quite challenging because the demands for uniformity over a larger area are difficult to accommodate as requirements on the device processing are much more stringent. In

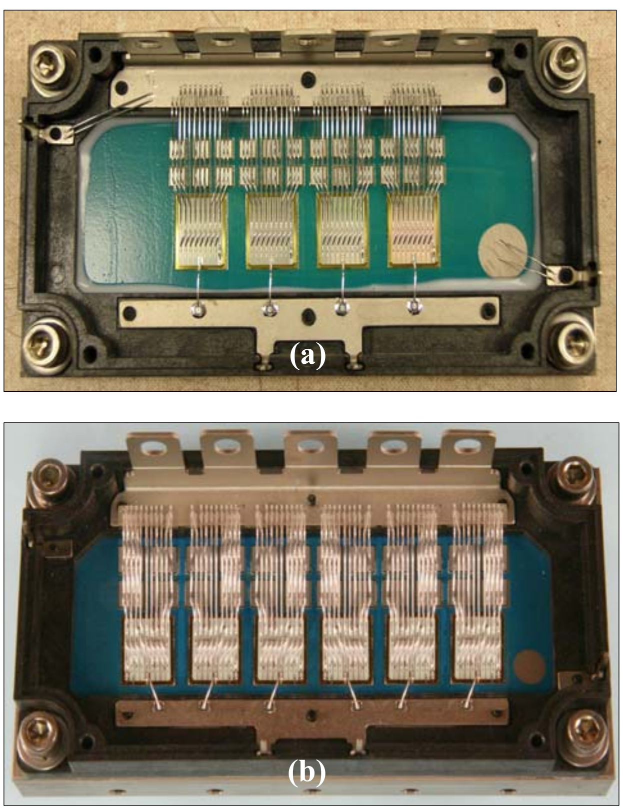

Fig. 14. Photographs of an (a) 1200 V, 500 A and (b) 1200 V, 900 A modules containing silicon IGBT switches and SiC JBS diodes.

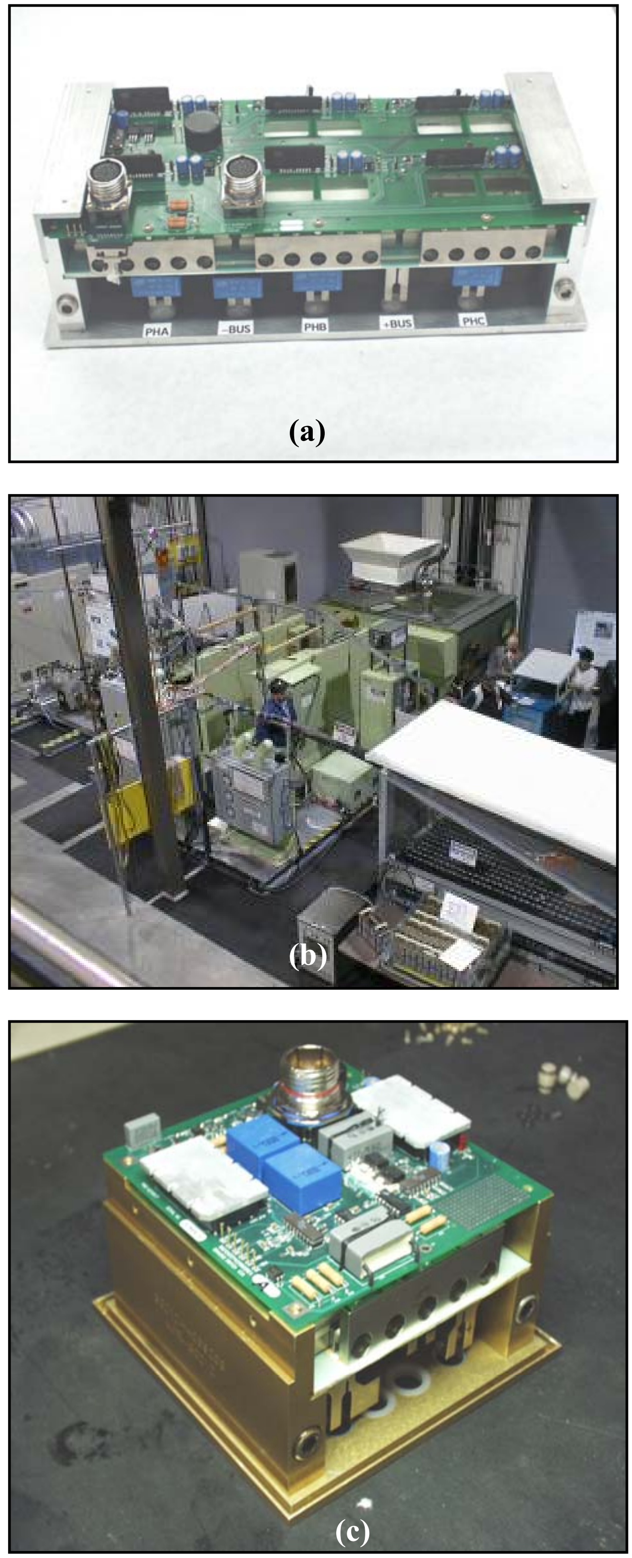

Fig. 15. Photographs of (a) a 3-phase inverter that will be tested using the modules with the SiC diodes, (b) the SIL where the testing will take place, and (c) single phase brake module where the diodes will be used in the future.

addition, the growth of SiC crystals has not yet completely matured so the SiC wafer can contain wafers with defects that cause premature breakdown. Increasing the area, increases the probability this will happen.

The P&E CTA has worked closely with the people at the Army Research Laboratory (ARL) who have an MTO along with TARDEC for the insertion of SiC devices into hybrid electric vehicles. One of the applications is the three phase inverter shown in Fig. 15a. Had the CTA continued, the next step was to insert the modules into the circuits used in the inverter and tested it at the Systems Integration Lab (SIL) pictured in Fig. 15b. Another potential application would have been the single phase break switch module shown in Fig. 15c. Of course, the final goal is to insert these systems into a hybrid electric vehicle such as the one shown in Fig. 16, so it will run more efficiently and quietly with the electronics consuming less of the valuable space inside.

Fig. 16. A hybrid electric vehicle in which the inverter circuits with the SiC JBS diodes will ultimately be used.

Summary

We have demonstrated a vertically integrated program beginning with basic research on how to design and fabricate 4H-SiC JBS diodes and inserting them into modules that will ultimately enable hybrid electric vehicles to run more efficiently and quietly while at the same time having the electronics take up less of the valuable space inside. This was done by determining the optimum diode structure and engineering around the problem of ion implant induced persistent defects in the SiC. In parallel with these efforts the material quality and manufacturing processes were improved with additional support from the joint ARL/TARDEC MTO. The diodes were placed in modules and tested and compared with modules using the traditional fast silicon diodes; the modules with the SiC diodes were shown to be able to operate at frequencies five time those using the silicon diodes, and they were also shown to operate more efficiently, as they had virtually no reverse bias stored charge that is eventually turned into heat. Modules with diodes having larger breakdown voltages and current carrying capacities had been fabricated when this program ended. Work is still ongoing in academia on trying to improve the quality of the JBS diodes by replacing the ion implanted P^+ channels with channels that have been grown selectively with the aid of a TaC protective cap.

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Army Relevance for the Future Force
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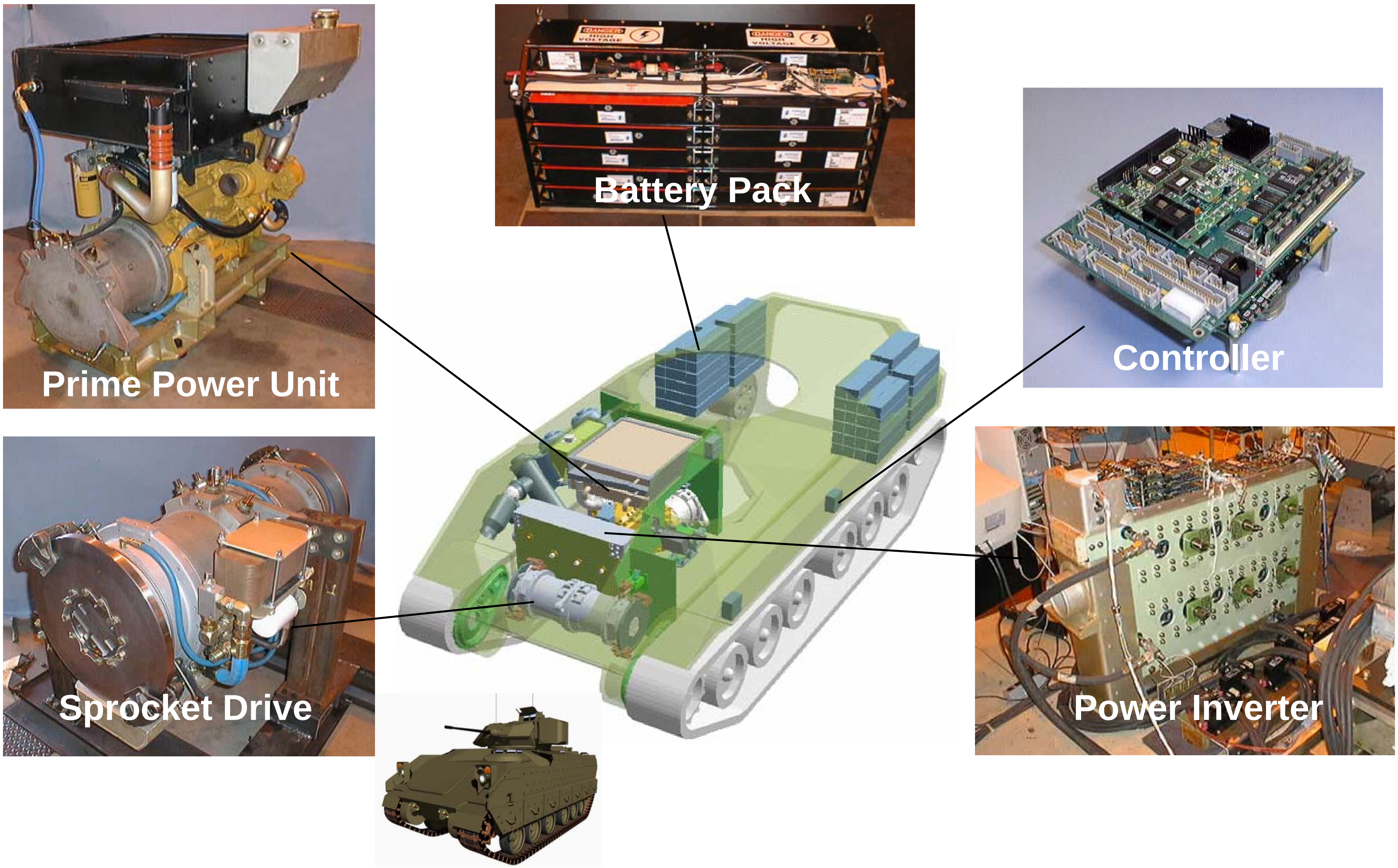
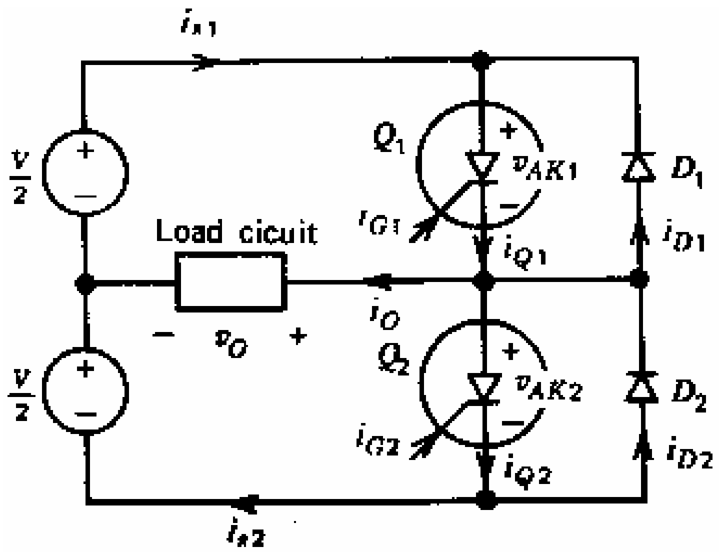
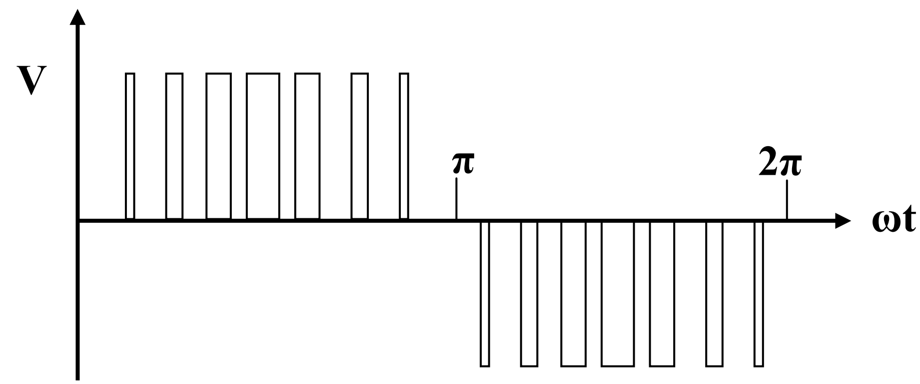


DC to AC Conversion





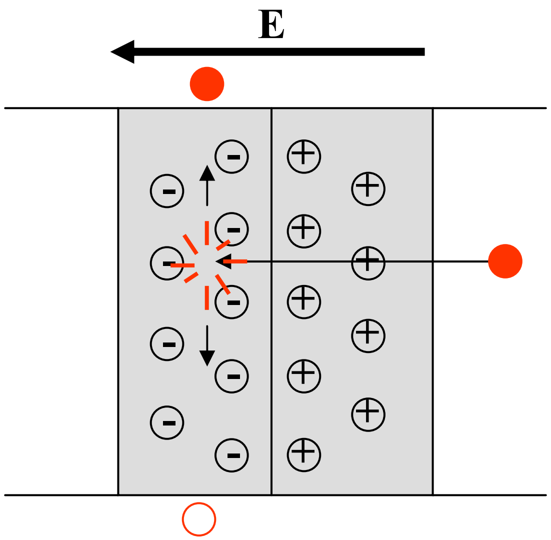
INVERTER CIRCUIT

1. When transistor Q_1 is on and Q_2 is off, the current i_0 is positive.
2. When transistor Q_1 is off and Q_2 is on, the current i_0 is negative.
3. The diodes carry the current until i_0 reverses because current can only flow one way through the transistor.

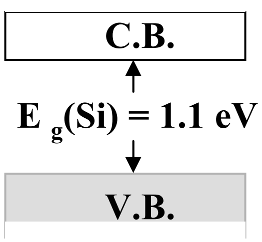
PULSE CODED MODULATION

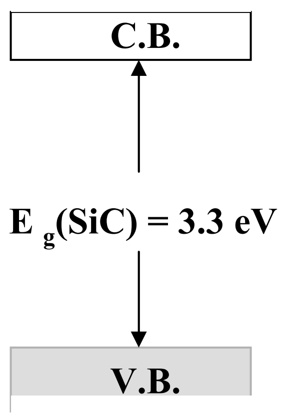
1. A series of rectangular voltage pulses is used to create a sinusoidal output.
2. The larger the number of pulses, i.e. the faster the circuit can be switched, the more accurately can the sine wave be approximated.

Desirable Diode Properties



Avalanche Breakdown





$V_{BR} = (\varepsilon E_C^2)/(2qn_d)$

$W_d = 2V_{BR}/E_C$

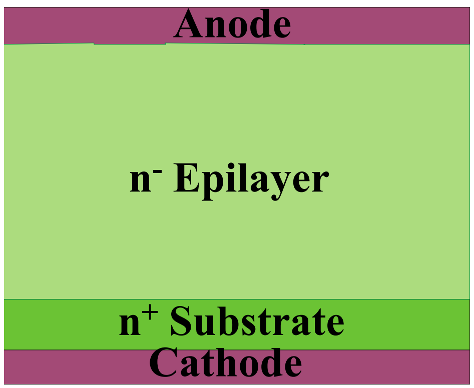
Energy Gap of Si and SiC

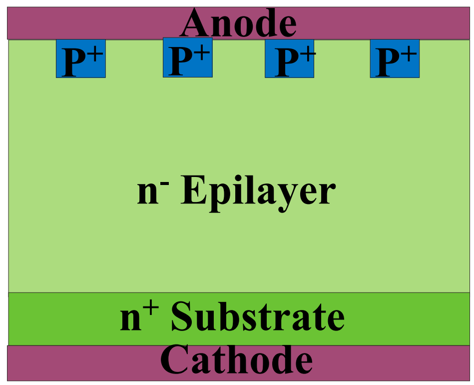
DESIREABLE PROPERTIES

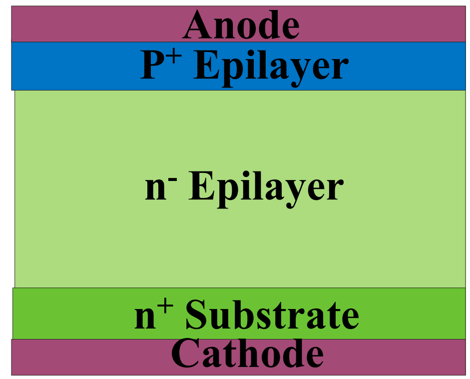
1. Relatively large breakdown voltage, V_{BR}
   - a. Electric field at junction cannot exceed E_C
   - b. E_C ten times larger in SiC than Si
   - c. Can achieve same V_{BR} in Si with n_d 100x less
   - d. Lower n_d leads to slower, higher loss device
2. Fast switching diode
   - a. Lower losses during switching
   - b. Better wave forms with higher frequencies
   - c. Si cannot be fast AND have a large V_{BR}
3. Want to be able to operate at higher Temp.
   - a. Like to be able to cool devices with engine oil
   - b. Eliminates noisy, large volume cooling app.
   - c. With small E_g Si cannot operate with T>150ºC
4. * Very thick films required for very large V_{BR}
   - a. Film thickness > depletion layer thickness W_d
   - b. Silicon film prohibitively thick

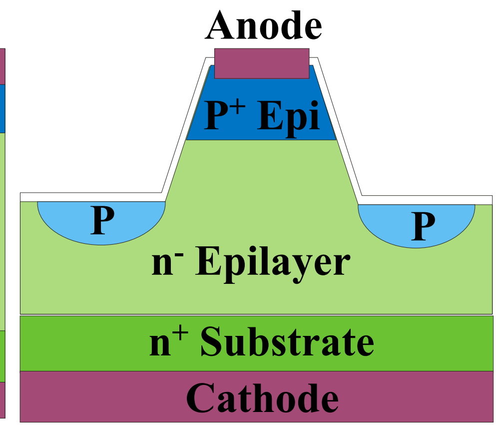
* Doesn't apply to this project

Types of SiC Diodes









Schottky

Advantages

- Fast reverse recovery behavior.

Disadvantages

- High reverse leakage current
- Soft breakdown causes excessive power dissipation

JBS

Advantages

- Lower leakage current so lower power dissipation
- Lower forward voltage drop than PiN

Disadvantages

- Larger forward voltage drop than Schottky

Implanted PiN

Advantages

- Lower forward voltage drop above 3 kV
- Potential for planar technology

Disadvantages

- Larger forward voltage drop below 3 kV
- Ion implanted defects are retained
- Potential for V_f drift

Epitaxial PiN

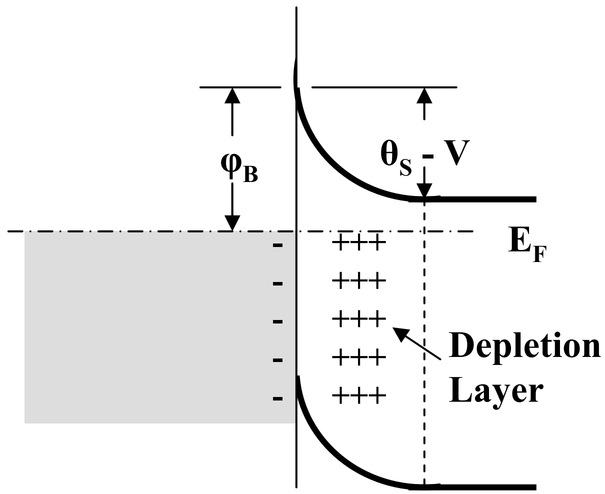
Advantages

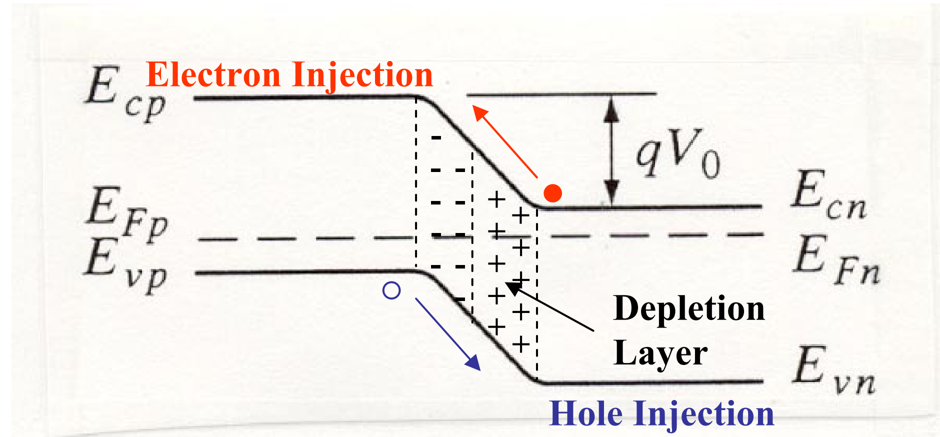
- Lower forward voltage drop above 3 kV

Disadvantages

- Larger forward voltage drop below 3 kV
- Uses nonplanar technology
- Potential for V_f drift

Schottky and PN Diodes





SCHOTTKY DIODE

1. Many electrons injected from semiconductor into the metal under forward bias, virtually none under reverse bias.

2. There are no holes so there is no minority carrier injection. No EHP recombination so faster and no stacking fault generation.

3. Depletion layer narrower under forward bias, wider under reverse bias.

4. Poor quality interface allows for large leakage current under reverse bias.

PN DIODE

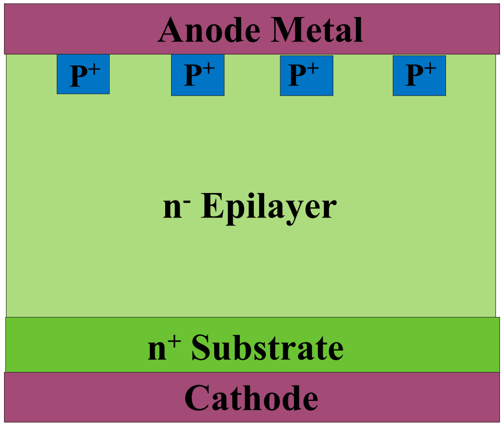
1. Many electrons injected into p-type material and many holes injected into n-type material.

2. There is minority carrier injection under forward bias that have to recombine, and this takes time, which slows the device down.

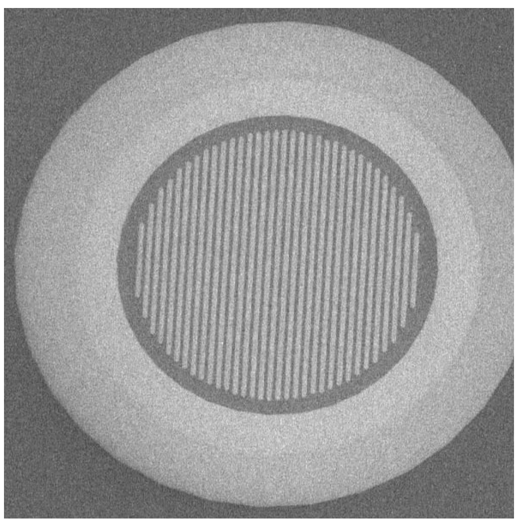
3. The energy produced by EHP recombination can produce stacking faults, which cause drift in the forward bias characteristics.

4. Depletion layer narrower under forward bias, wider under reverse bias.

The JBS Diode



Schematic of Side View

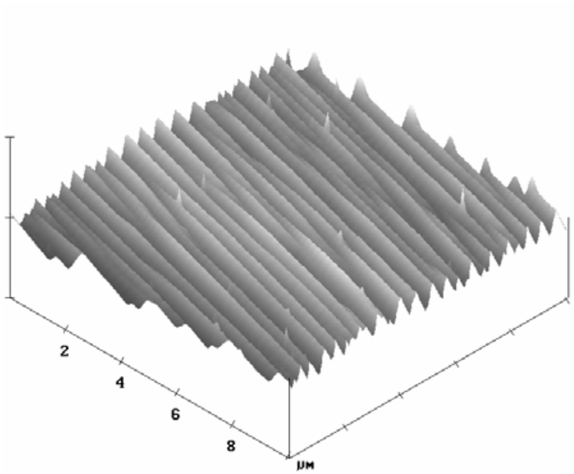


Top View of an Implanted Device

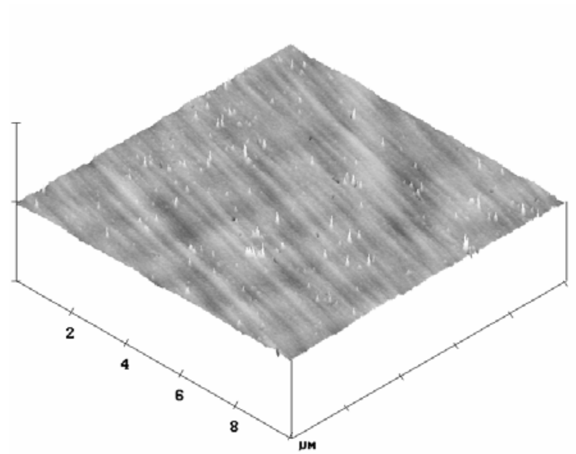
JBS DIODE FABRICATION ISSUES

1. The JBS diode behaves like a Schottky diode under forward bias. The voltage across the junction is too low to 'turn on' the P^+n^- diode.
2. The JBS diode behaves like a PN diode in reverse bias because the depletion layers from the P^+ layers block the flow to the Schottky metal.
3. The P channels are formed by ion implantation.
4. The damage created by the implant process has to be annealed out to activate the implanted ions.
5. At the temperature required to anneal out the implant damage, the silicon evaporates preferentially and damages the device.
6. We have developed a BN/AlN annealing cap that blocks the silicon evaporation and can be removed after the anneal without harming the device.

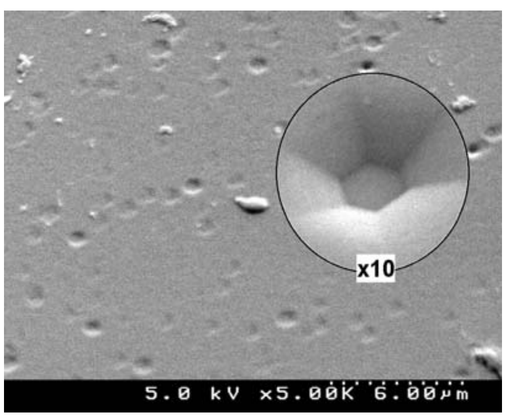
BN/AlN Annealing Cap



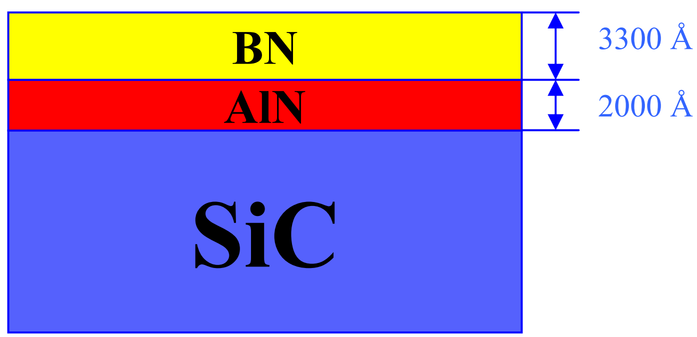
Uncapped Anneal



Capped Anneal



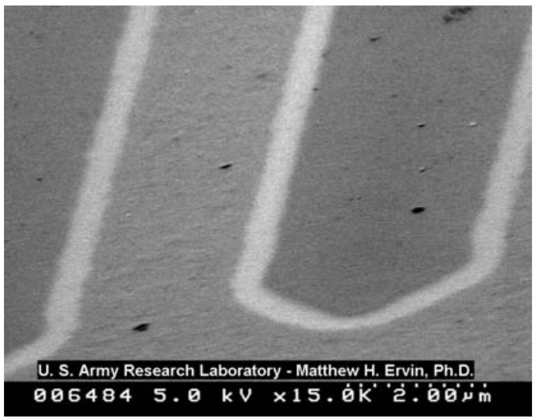
AlN Cap Begins to Evaporate at 1650º

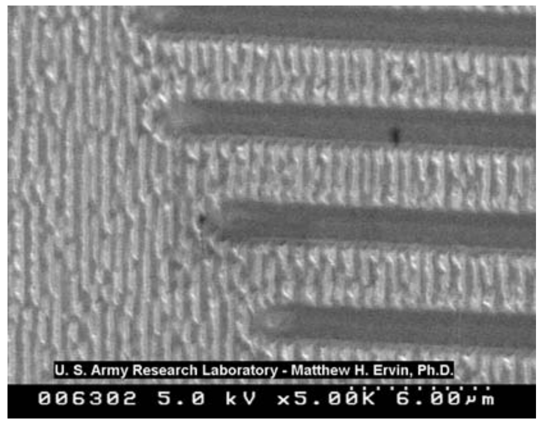


BN/AlN cap

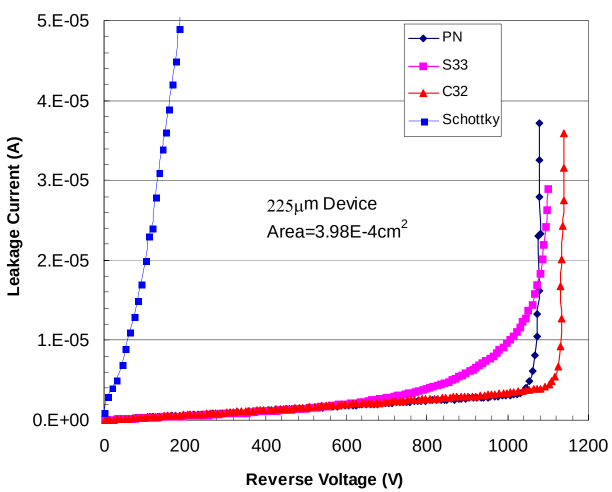
1. The surface of the sample annealed with no cap is rough.
2. The surface of the sample annealed with a cap is smooth.
3. The AlN cap can be etched off in warm (80º) KOH.
4. There is no in-diffusion of Al or N during the anneal and warm KOH does not etch SiC.
5. For T > 1600ºC the AlN has to be capped with BN.
6. BN cannot be chemically etched off; it is ion milled off, and then the AlN is chemically etched off.

Improved Device Performance by Annealing with an AlN Cap

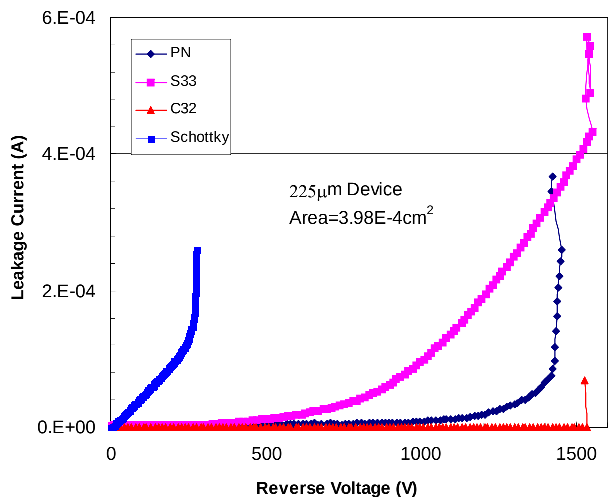




AlN capped anneal has produced JBS leakage currents that have only been matched by Infineon.



Annealed with AlN cap at 1600°C

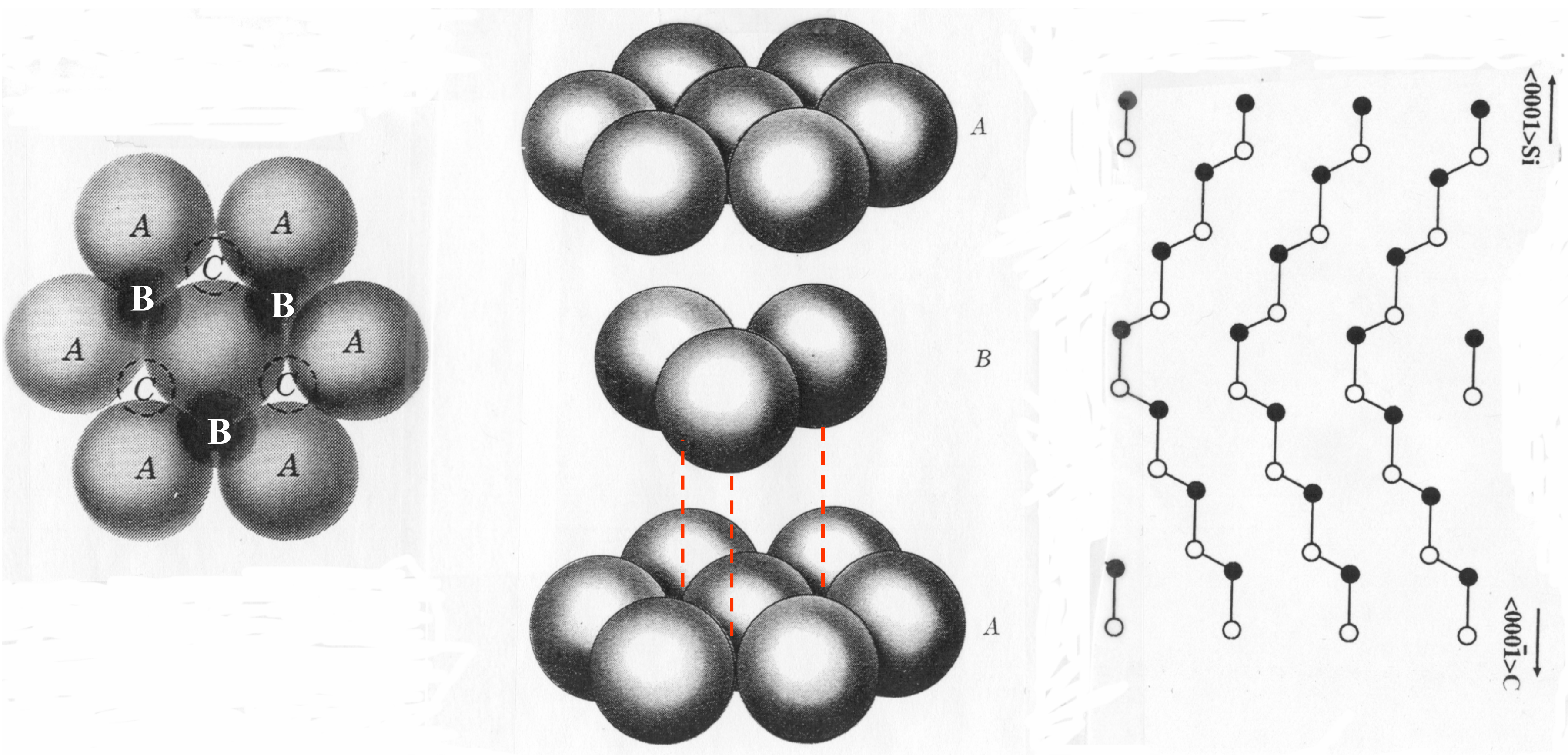


Annealed in SiH_4 at 1600°C

After we solved the surface problem we discovered that ion implantation produces persistent defects.

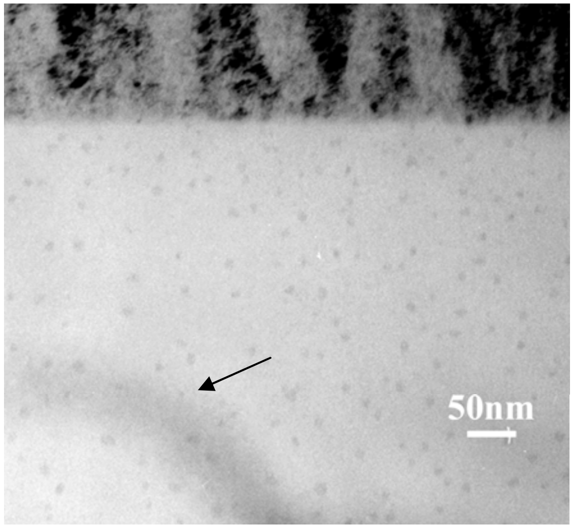
SiC Polytypes

SiC has over 200 polytypes - hard to grow the one you want!

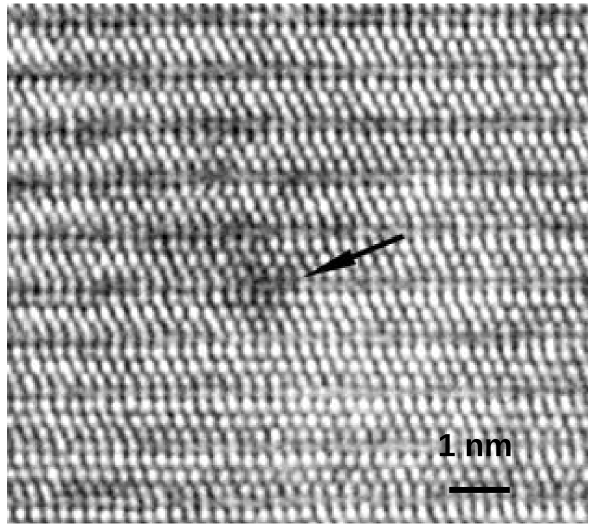


3C 2H 6H

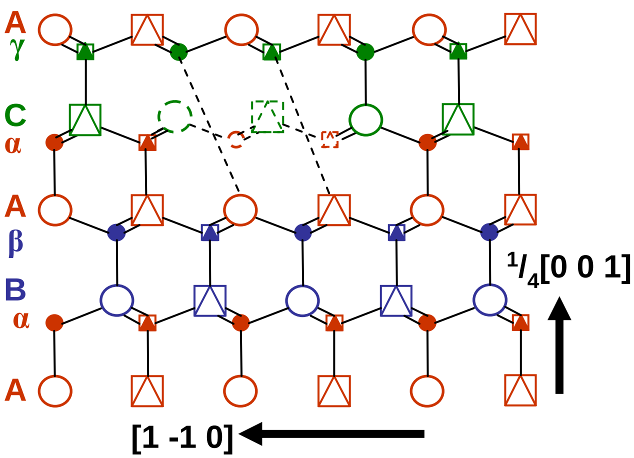
Persistent Ion Implanted Defects



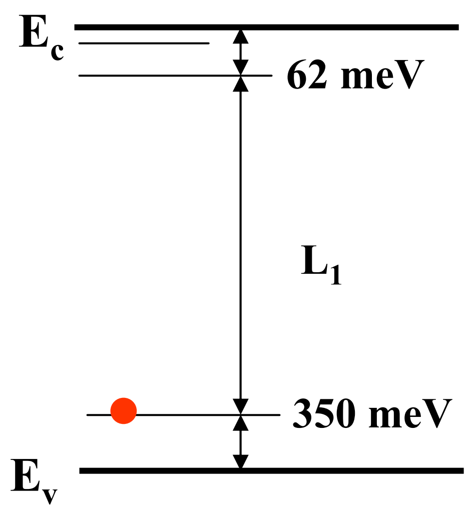
TEM Showing Defects (spots)



HRTEM of Spots Showing SF



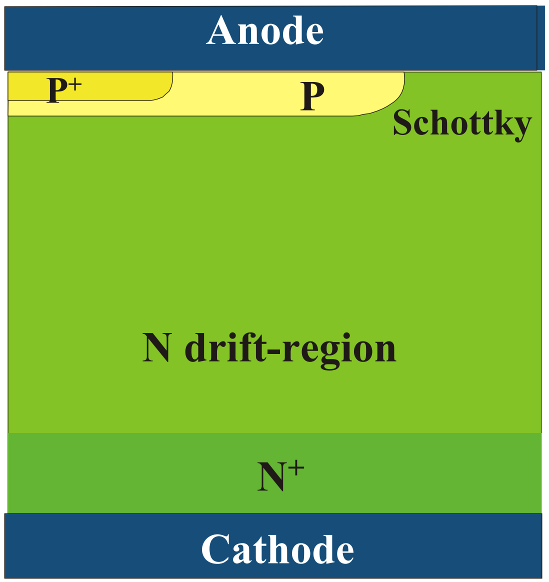
Schematic of Frank intrinsic SF formed by the condensation of divacancies.

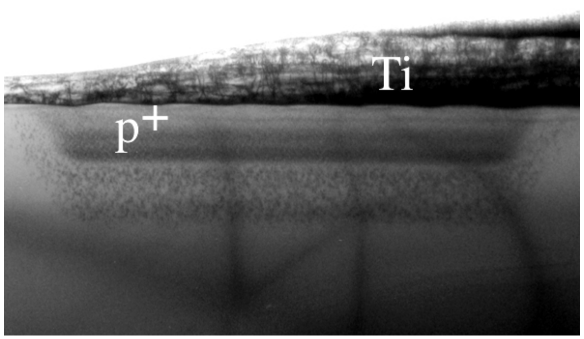


Janzen, et al theory that defect is a deep donor

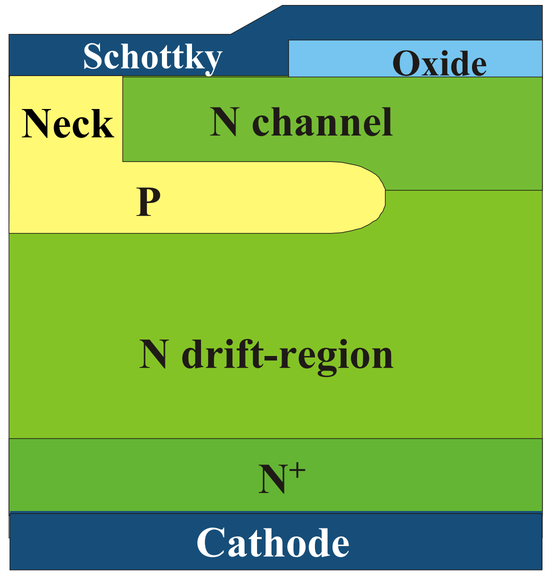
1. TEM shows that annealed ion implanted region contains persistent defects that nucleate and grow.
2. HRTEM show that defects are stacking faults.
3. Defects thought to be associated with divacancies; a Frank intrinsic stacking fault can be formed by the condensation of divacancies.
4. The defect is thought to have energy states in the energy gap associated with it.
5. One possibility is that it is a deep donor that can trap out holes in the valence band.

Compensation and Alternative Solution





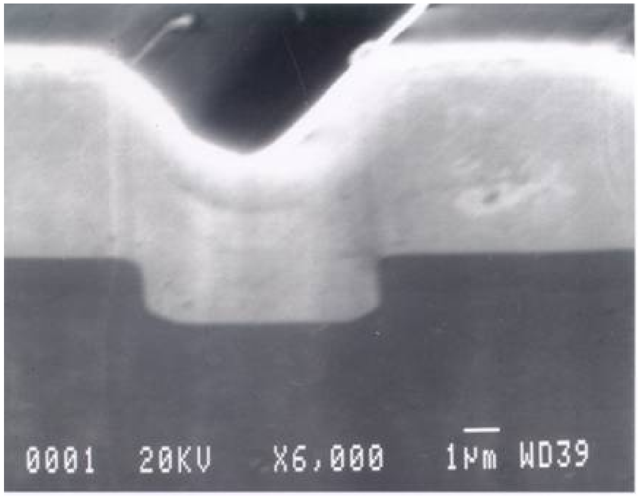
High/Low, Shallow/Deep Implantation Dose



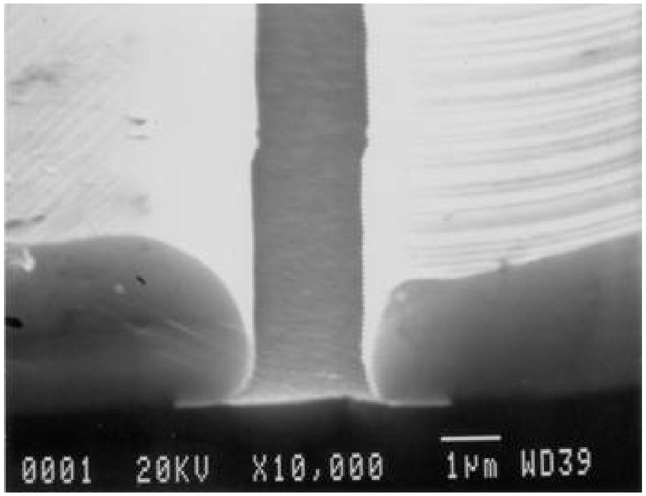
Regrow over implanted P region and implant neck

1. Implant heavy near contact and lighter near junction to reduce the number of defects in the depletion region.
2. The reduction in the number of defects more than compensates for the disadvantage of the lower doping level.
3. The diode with the regrown channel and the implanted neck can more easily pinch off the Schottky diode connection so it has a lower leakage current.

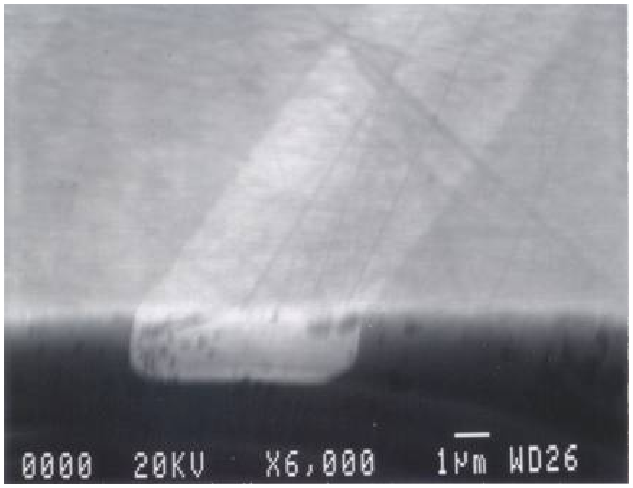
Regrowth or Selective Area Growth of P^+ Channel Using TaC Shield



Etch and regrow p+ film



Selective area growth with patterned TaC cap



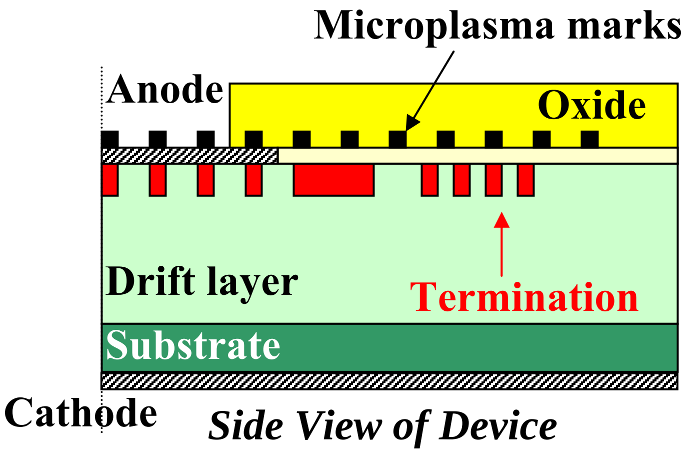
Polish regrown film

1. **Etch rectangular channels in the n-drift film.**
2. **Regrow P^+ film over the entire wafer.**
3. **Polish off the P^+ film so that only the filled channels remain, but there is polishing damage on the surface.**

OR

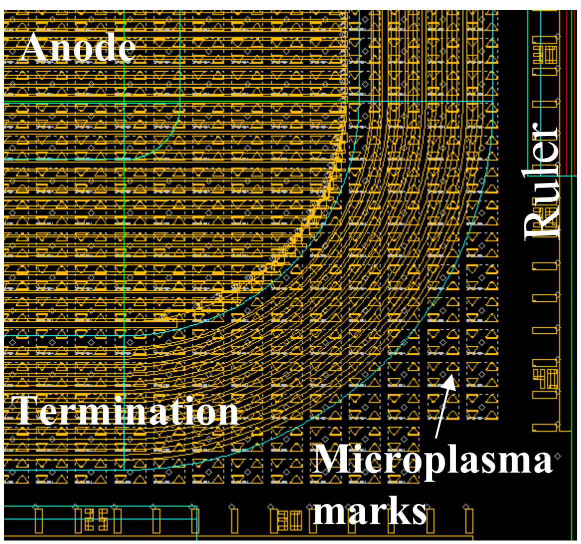
4. **Protect the Schottky regions with TaC and selectively grow SiC only in the channels.**
5. **Etch away the TaC after growth of the P^+ channels.**

Premature Breakdown in Implanted Guard Rings

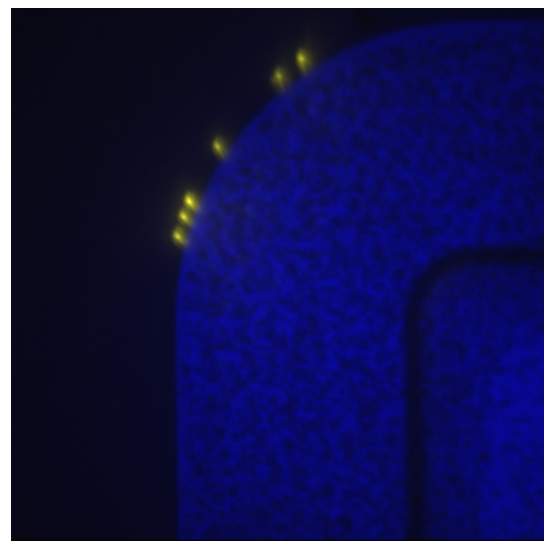


Side View of Device and Guard Rings

1. Guard rings are necessary to prevent premature breakdown at the edges.
2. Guard rings are implanted.
3. There is a possibility of premature breakdown caused by the persistent defects caused by ion implantation.

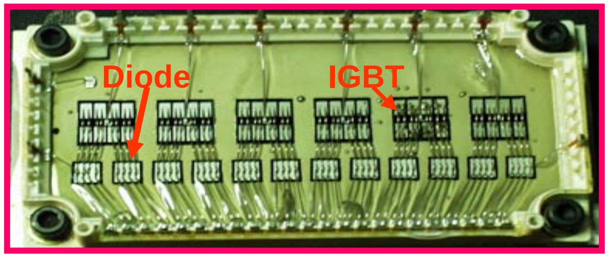


Top View of Device and Guard Rings

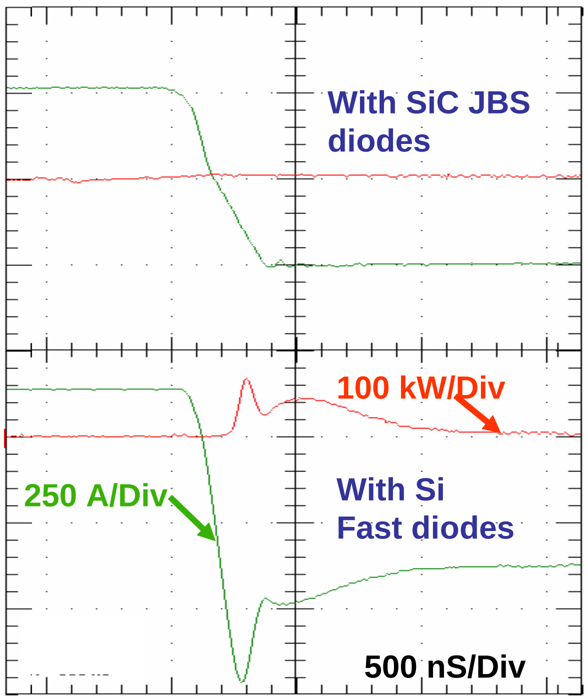


Top View of Device with Microplasmas

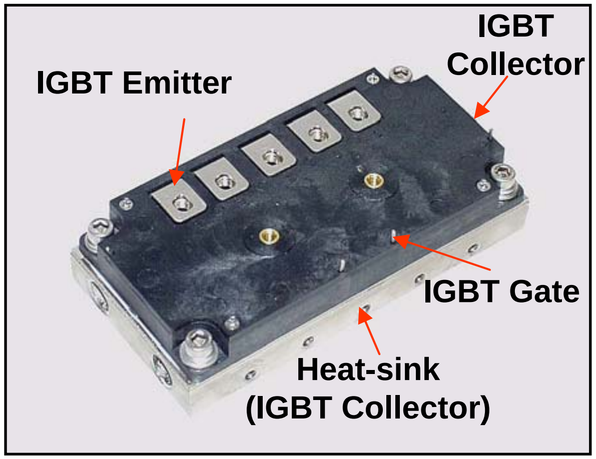
SiC JBS Diodes Produce Superior Circuit Properties



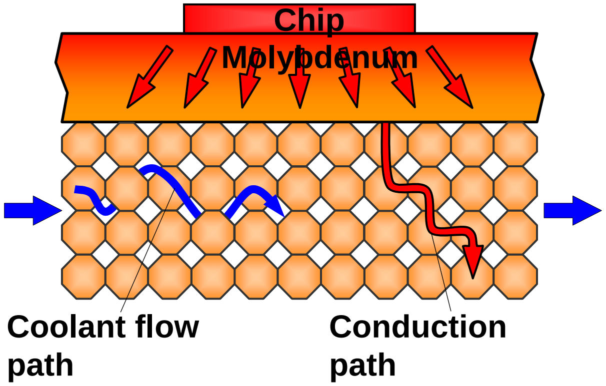
600 A, 550 V Module with SiC JBS Diodes and Si IGBT's



Characteristics of Module Using SiC JBS or Fast Si Diodes



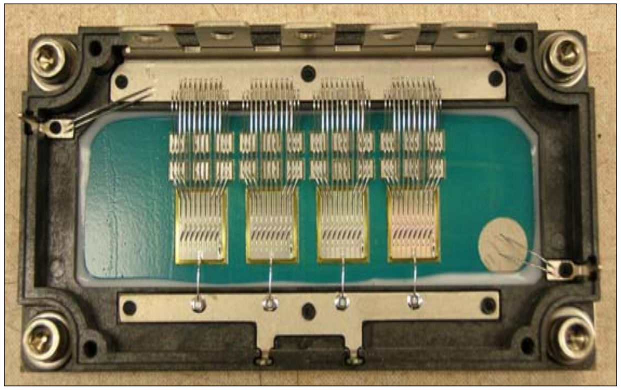
Module mounted on a Heat Sink



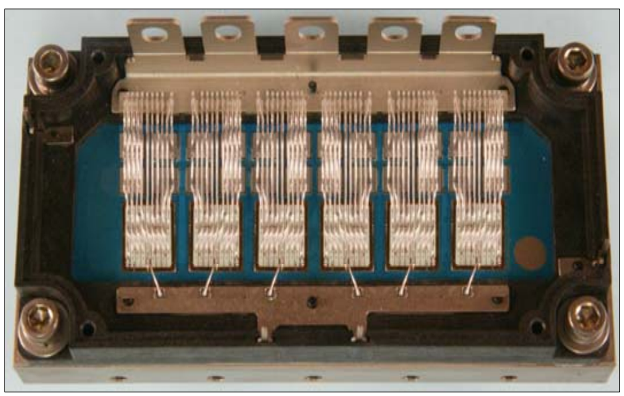
Heat sink we developed for the module

1. The module tested with both SiC JBS and Si fast diodes show that the SiC diodes produce superior results.
2. There are virtually no switching losses with the SiC diodes.
3. The heat sink developed for the modules enabled them to operate at a lower temperature.

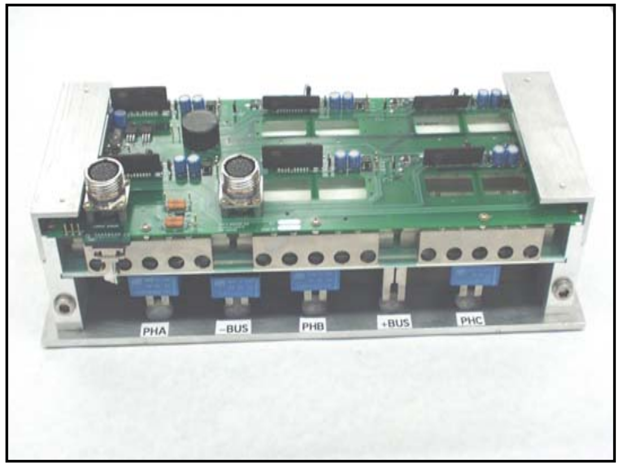
Module and Systems Where SiC JBS Diodes Will Be Used



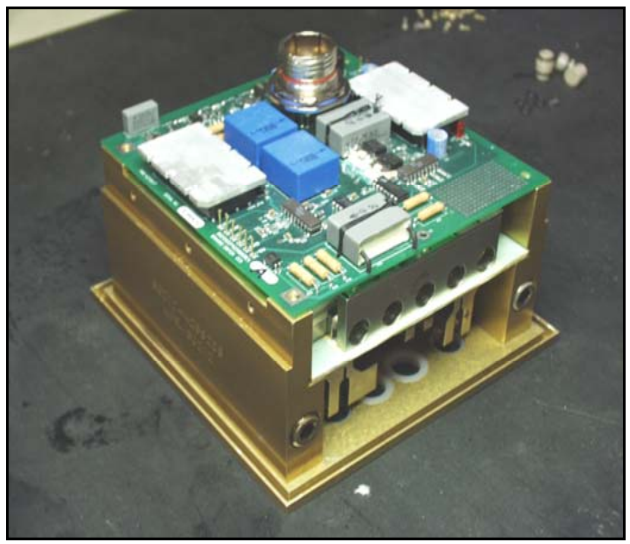
1200 V, 500 A Module



1200 V, 900 A Module



3 Stage Inverter using modules



Single Phase brake module using JBS diodes in the future

Systems Integration Lab (SIL) where the systems are tested

Conclusions

A hybrid electric vehicle in which the inverter circuits with the SiC JBS diodes will ultimately be used.

VERTICAL INTEGRATION

1. **We developed an understanding of the important material and device processing issues and found ways to work around them.**
2. **By understanding the material issues we were able to design, build and test JBS diodes that were matched by only one other source.**
3. **These ideas were taken up by a device manufacturer who was able to mass produce the devices.**
4. **The device manufacturer and the systems people worked with the module supplier to enable us to test the diodes we manufactured.**
5. **The systems integrator was able to insert the modules into an existing circuit, and was able to demonstrate that the efficiency of the circuit was improved by using the SiC JBS diodes instead of the fast Si diodes being used in the present systems.**